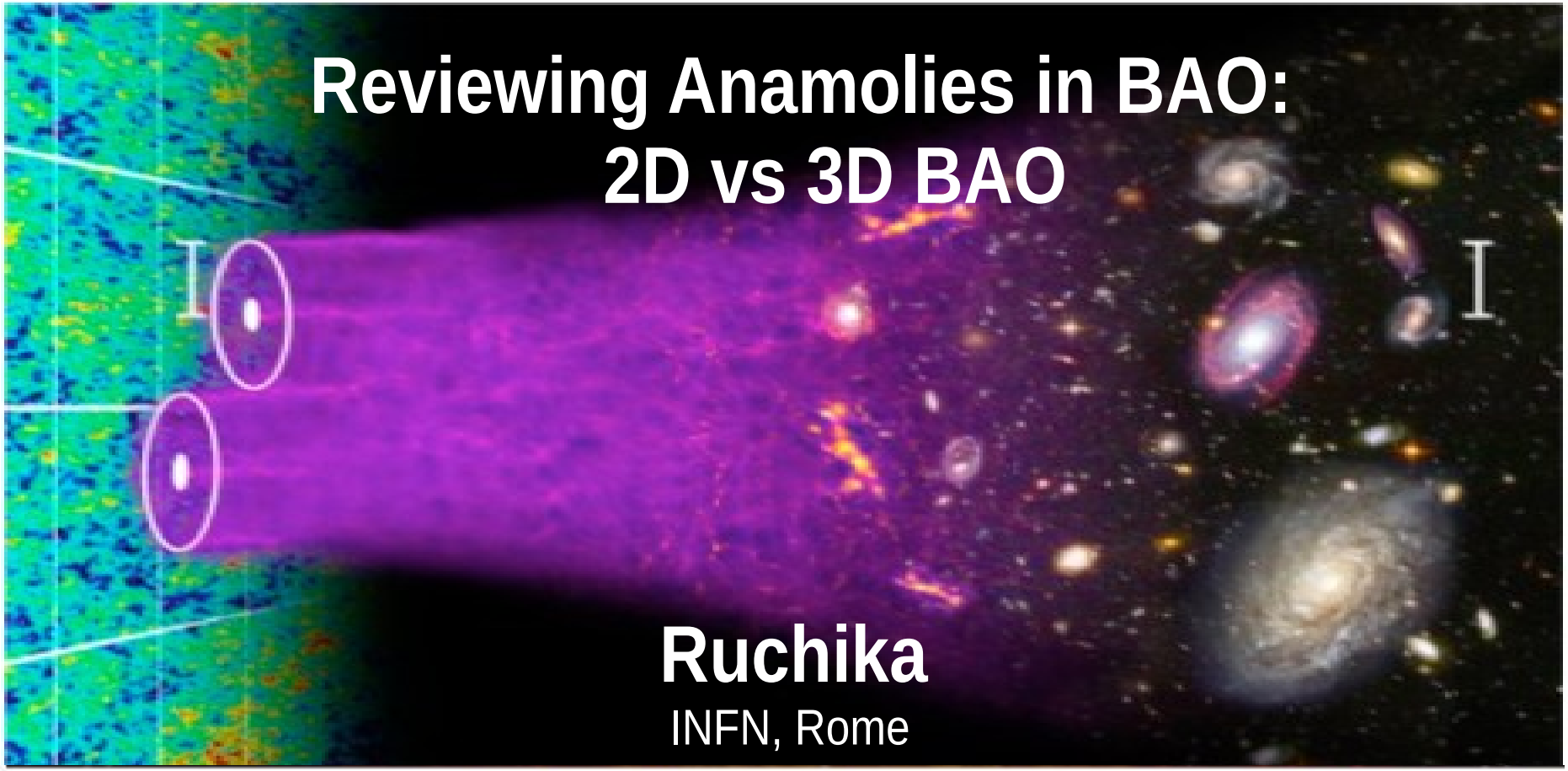


Reviewing Anamolies in BAO: 2D vs 3D BAO

Ruchika
INFN, Rome

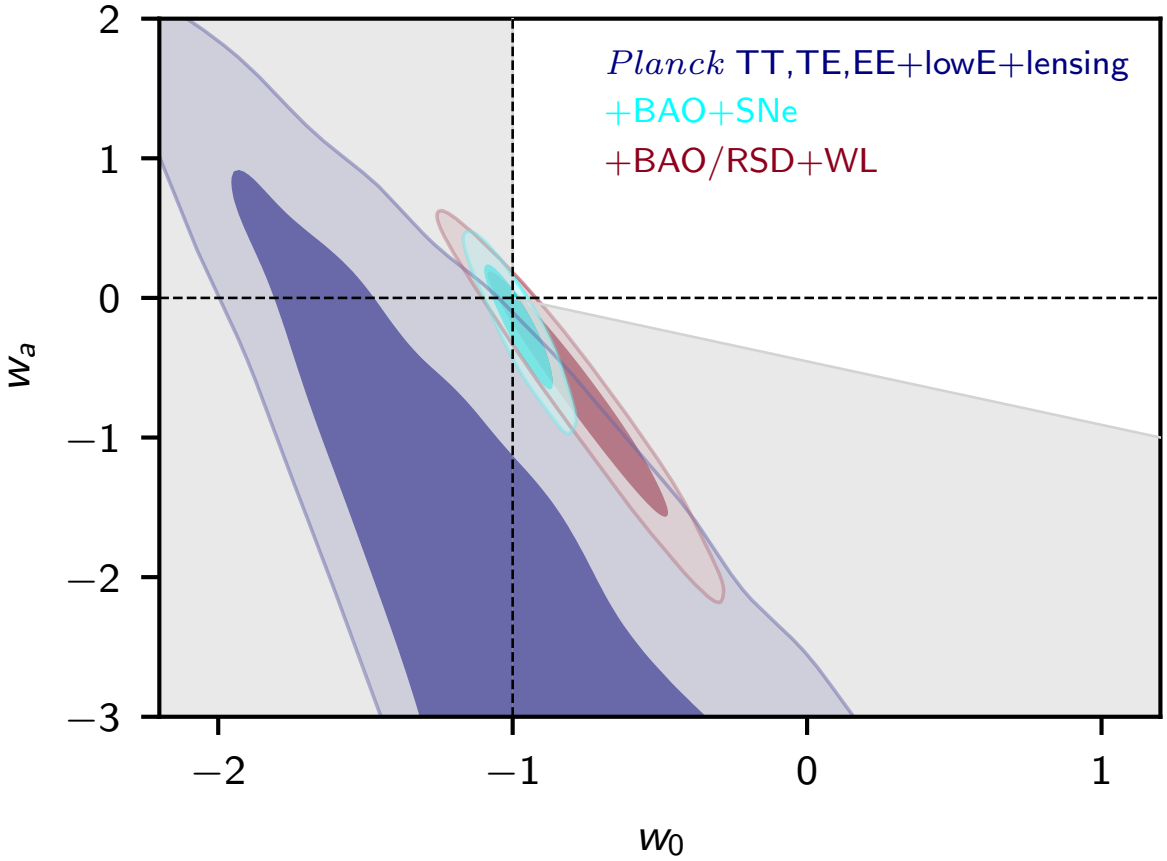
Outline of the Talk

- Planck 2018 Cosmology using CMB, BAO, Sne Ia
- Tensions in ΛCDM cosmology
- BAO data suggests the need for introducing Early Dark Energy
- 2D vs 3D BAO data
- DESI BAO Analysis
- Final Take away!

Observations ◇

Planck results 2018

CPL Parameterisation: $w = w_0 + w_a(1 - a)$



P.Ade et al. A&A, 2018

Result of Planck Observations ◇

Cosmological Constant is **Consistent** with
CMB+Bao+ SnIa

Then, Why beyond Λ?

Tensions in ΛCDM $\diamond$

- $\diamond$ Hubble Tension : Riess et al. vs Planck Collaboration
- $\diamond$ S_8 (growth rate) Tension : KiDS, DES, Planck Collaboration
- $\diamond$ Cosmic Dipole Tension : Various Teams including Geraint Lewis team
- $\diamond$ CMB anomalies : Planck Collaboration, SPT and ACT
- $\diamond$ ISW (Integrated Sachs-Wolfe) Tension : Various Teams including A. Kovacs team
- $\diamond$ Lithium Problem : Primodial Nucleosynthesis

Tensions in ΛCDM ◇

◇ Hubble Tension : Riess et al. vs Planck Collaboration

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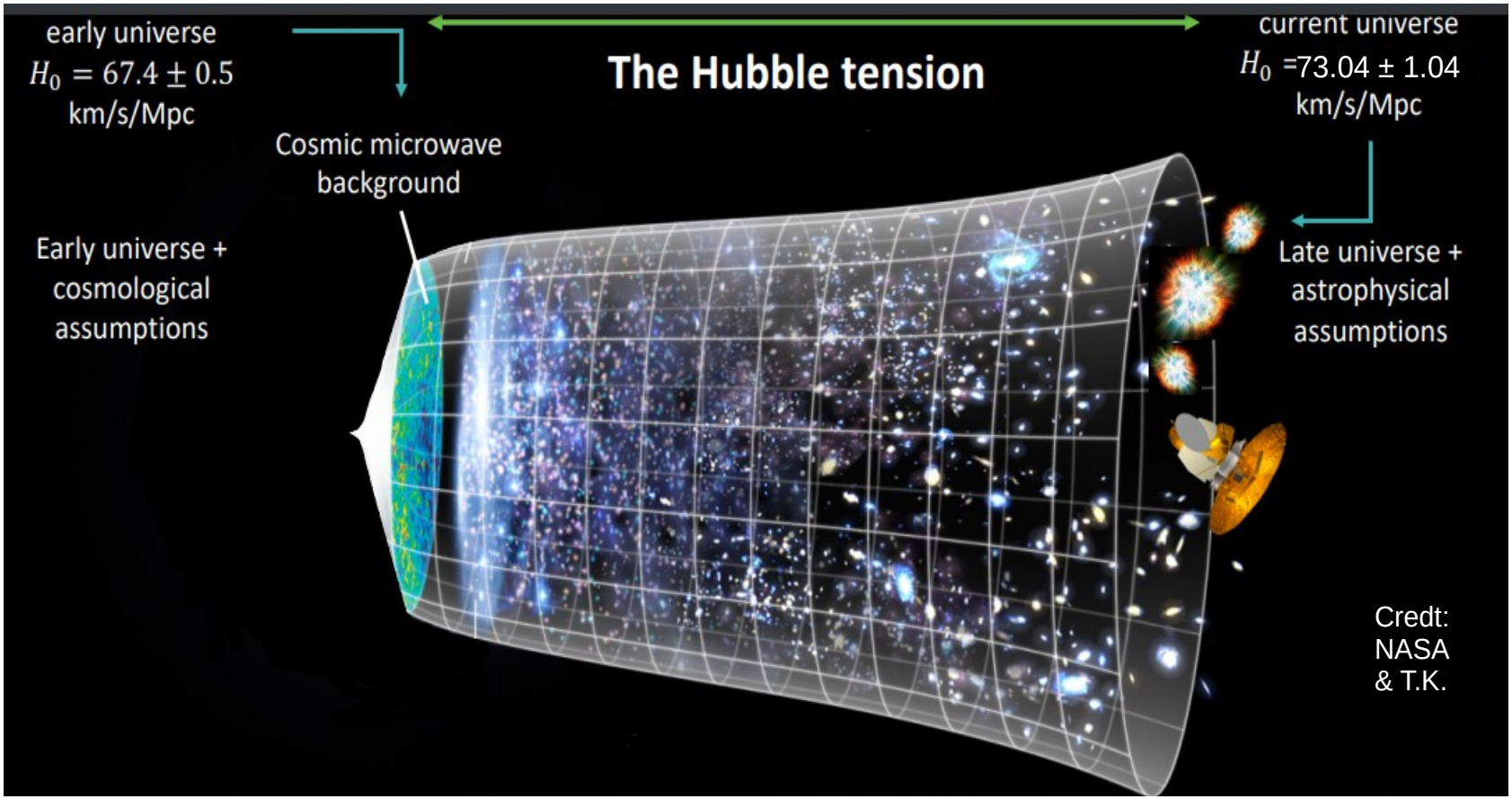
◇ ISW (Integrated Sachs-Wolfe) Tension : Various Teams including A. Kovacs team

◇ Lithium Problem : Primodial Nucleosynthesis

◇ **BAO Anomalies** : **...**

Present situation ◇

> 5 sigma



Standard Objects: CMB Baryon Acoustc Oscillations Cepheids +SN Type Ia

What and how BAO adds to the present situation?$\diamond$

Reminder:
r_d and H_0 provide absolute scales for distance measurements (anchors) at opposite ends of the observable Universe.

Let us ask ourselves these questions.

- Is H_0 tension correlated to any other Cosmological Parameter?
  $\rightarrow$ Answer is: Yes, Since BAO measures the combination of $r_d H_0$.

- Can we break this degenracy of $r_d H_0$ and how?
  $\rightarrow$ Answer is: Yes, If we can measure H_0 independently, then one can estimate r_d.

Data Used and Results ◇

Data used :

BAO from 6dF, MGS, eBOSS, BOSS DR12 including Lyman-alpha forest sample.
Time-delay distance measurement through Strong Lensing by H0LiCOW measurements.
Angular Diameter Distances for galaxies UGC3789, NGC6264 and NGC5765b.
Taking value of $H_0 = \mathbf{73.24 \pm 1.24\ Km/s/Mpc}$ from Riess et al. (2016)

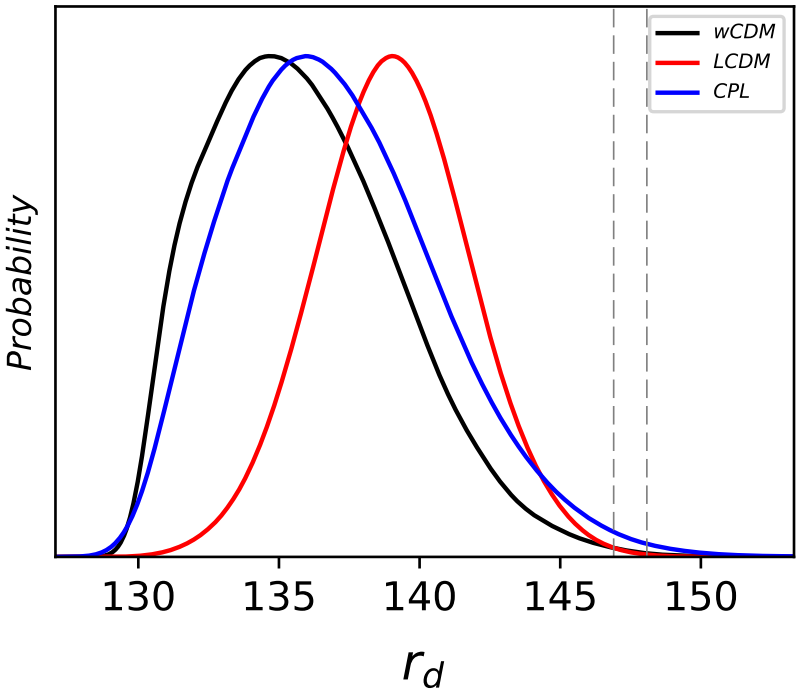
Results :

Maximum Likelihood values and 1D marginalised 68% confidence interval

	$\Omega_m 0$	r_d	w_0	w_a
ΛCDM	0.295 ± 0.019	139.2 ± 3.2	N/A	N/A
wCDM	0.277 ± 0.027	135.3 ± 3.8	-0.76 ± 0.14	N/A
CPL	0.241 ± 0.084	136.4 ± 3.9	-0.77 ± 0.17	0.44 ± 0.53

Also, $r_d = 136.41 \pm 3.82$ Mpc confirmed in a cosmology model independent way.
Reference: Jarah Evslin, A.A.Sen, **Ruchika**, Phys. Rev. D 97,103511(2018)
Reference: Salvatore Capozziello, **Ruchika**, A.A. Sen, MNRAS 484 (2019) 4484

Results ◇



$r_d = 147.26 \pm 0.29 Mpc$ (Planck)

- ΛCDM: 2.52 σ away from Planck
- wCDM : 3.14 σ away from Planck
- CPL : 2.79 σ away from Planck

So, our results are quite model independent.

So, The Price of shift in Hubble constant is the shift in r_d.

Results ◇

	Planck		Local Measurements
H_0	$67.37 \pm 0.54 Km/sec/Mpc$	$\Rightarrow$	73.24 ± 1.24 Km/s/M pc.

Results ◇

	Planck		Local Measurements
H_0	$67.37 \pm 0.54 Km/sec/Mpc$	$\Rightarrow$	73.24 ± 1.24 Km/s/M pc.
r_d	$147.26 \pm 0.29 Mpc$	$\Leftarrow$	$139.2 \pm 3.2 Mpc$

- To find Early Universe solutions to Hubble Tension or to increase H_0 at high redshift, we need to decrease r_d around recombination.

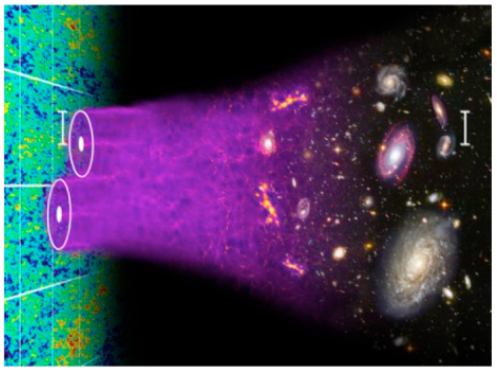
Interpretation ◇

$$r_d = \int_0^{t(zd)} c_s(1+z)dt$$

Physics: sound waves in early Universe propagate until radiation and matter decouple.

Lower r_d as compared to Planck suggets:

◇ changing z_d
◇ modifying the speed of sound
◇ changing primodial fluctuations
◇ changing the age of universe at drag epoch



Credit: Blake & Moorfield

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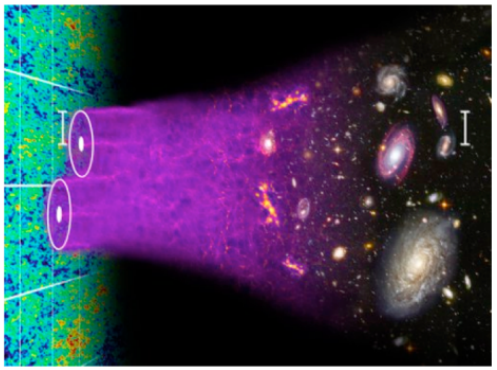

Credit: Blake & Moorfield

$$r_d = \int_{z\star}^{\infty} dz \frac{c_s(z)}{H(z)}$$

Conclusion ◇

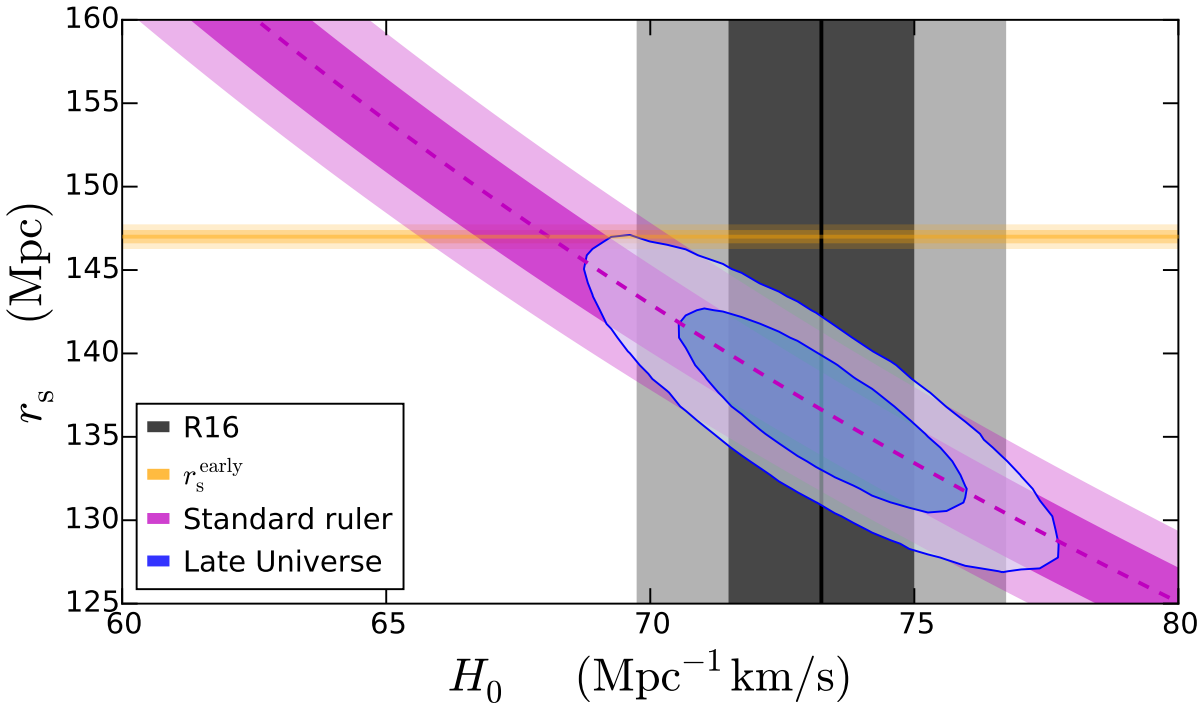
◇ Along with Hubble Tension, there is a similar tension involving sound horizon at drag epoch from low-redshift and Planck measurements.

◇ It does not depend on dark energy behaviour.

◇ Since r_d is governed by early universe physics, to reduce r_d or to increase H_0 around recombination, One needs to modify the early universe cosmology.

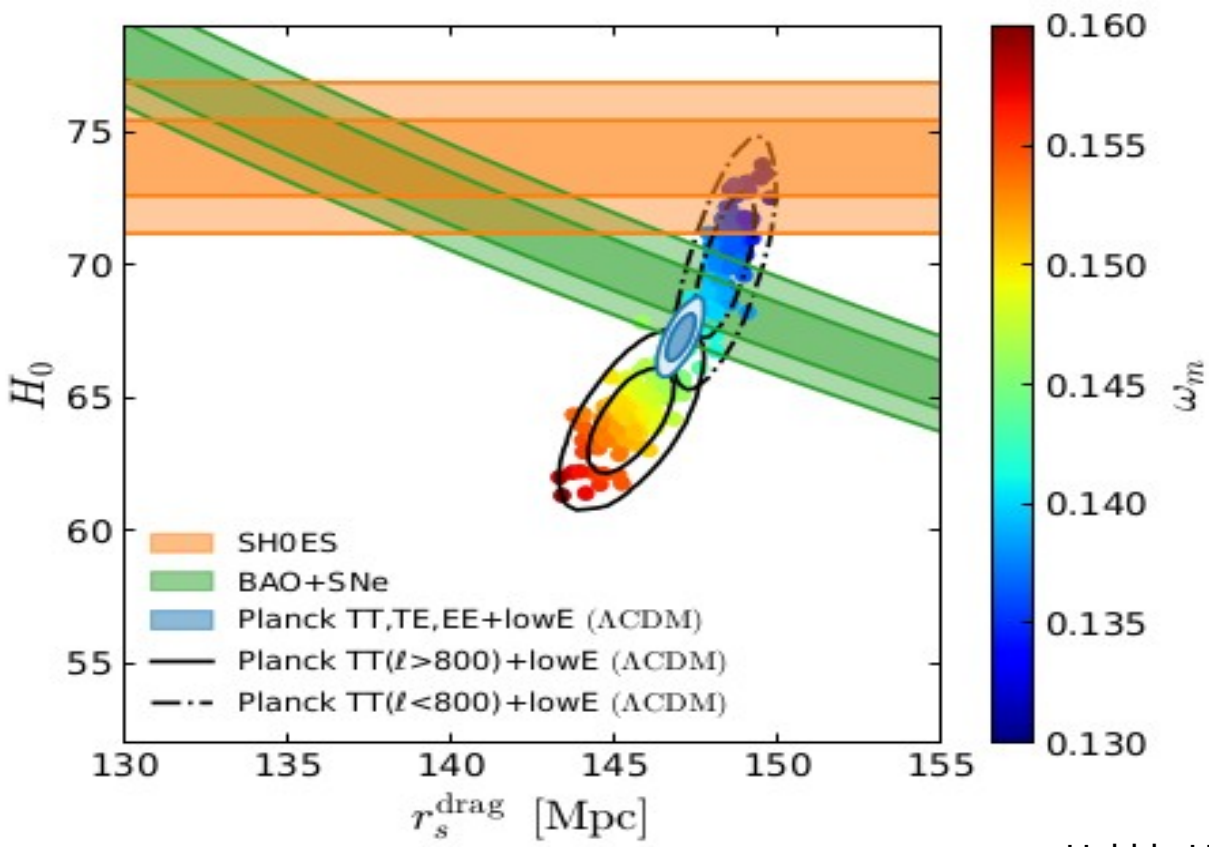
◇ **Solution : Early Dark Energy was proposed.**

Similar studies◇



Same is also seen by Bernal, Verde, Riess, JCAP 2016

Similar studies ◇



Hubble Hunter's Guide
Knox et al. 2019

 # Late Universe suggests : Price of shift in H0 is the shift in rd

Increase in H0 require decreased rd

Reviewing anomalies in 2D and 3D BAO Datasets Including DESI Release

(Trouble with Standard Cosmological Model?)

Arxiv: 2406.05453
Ruchika

Data and Observables ◇

Observables Used

- Luminosity Distance (measured)

$$M = m - 5\log_{10}\frac{D_L}{10\,\mathrm{pc}}$$

- Angular Diameter Distance & Volumetric Distance (inferred)

$$D_L = (1+z)^2 D_A\,, \quad D_H \;\&\; D_M(z).$$

$$D_V(z) = \left[(1+z)^2 D_A^2(z) z D_H\right]^{1/3}.$$

- 2D BAO measurements from angular separation of pairs of galaxies (measured)

$$\theta_{BAO}(z)[^\circ]$$

Data Used

- Supernoave Type-Ia

  Pantheon Plus Sample which comprises 1701 SNe data points ranging in the redshift interval $0.01 \leq z \leq 2.3$

- 3D BAO data including DESI

  Anisotropic: BOSS DR12
  Isotropic: 6dF, MGS, eBOSS

- 2D BAO data / Thin redshift slice

  11 θ _BAO (z) measurements obtained from public data of the Sloan Digital Sky Survey (SDSS), namely DR10, DR11, and DR12

Where is the fiducial cosmology incorporated? ◇

Measured Quantities

- Flux/Apparent Magnitude

measured

$$M = m - 5\log_{10}\frac{D_L}{10\,\mathrm{pc}}$$

- Ratio of Distances/ rd

measured

$$\alpha_\perp = \frac{D_M(z) r_{d,fid}}{D_M^{fid}(z) r_d}; \quad \alpha_\parallel = \frac{H^{fid}(z) r_{d,fid}}{H(z) r_d}$$

- Theta measurements

measured

$$\theta_{BAO}(z)[^\circ] = \frac{r_d}{(1+z)D_A(z)}$$

Data Used

- Supernoave Type-Ia

  MB used from both high and low redshift experiments.

- 3D BAO data

  Measures shift from fiducial cosmology parameters.

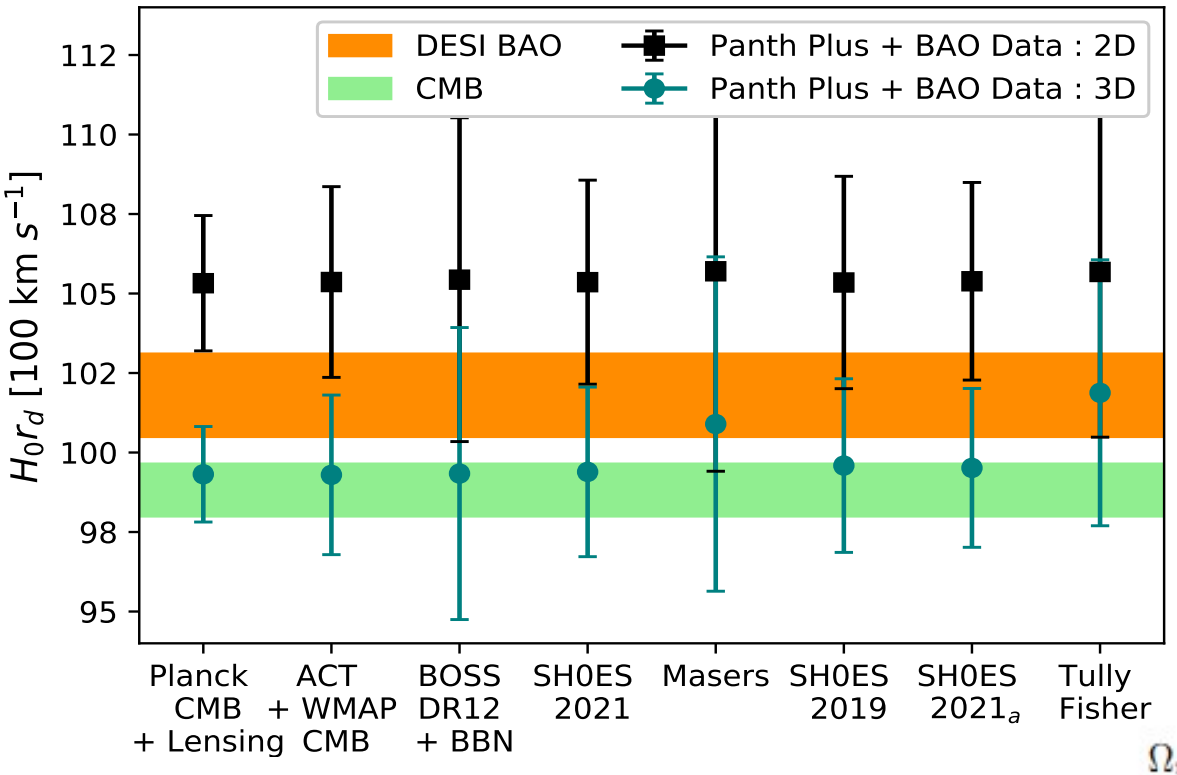
- 2D BAO data / Thin redshift slice

  Utilises fiducial cosmology to extract true bump theta.

Model Used:

$$\frac{H^2(z)}{H_0^2} = \Omega_{m0}(1+z)^3 + (1-\Omega_{m0}),$$

Results ◇



Assumption:
Standard Cosmological Model

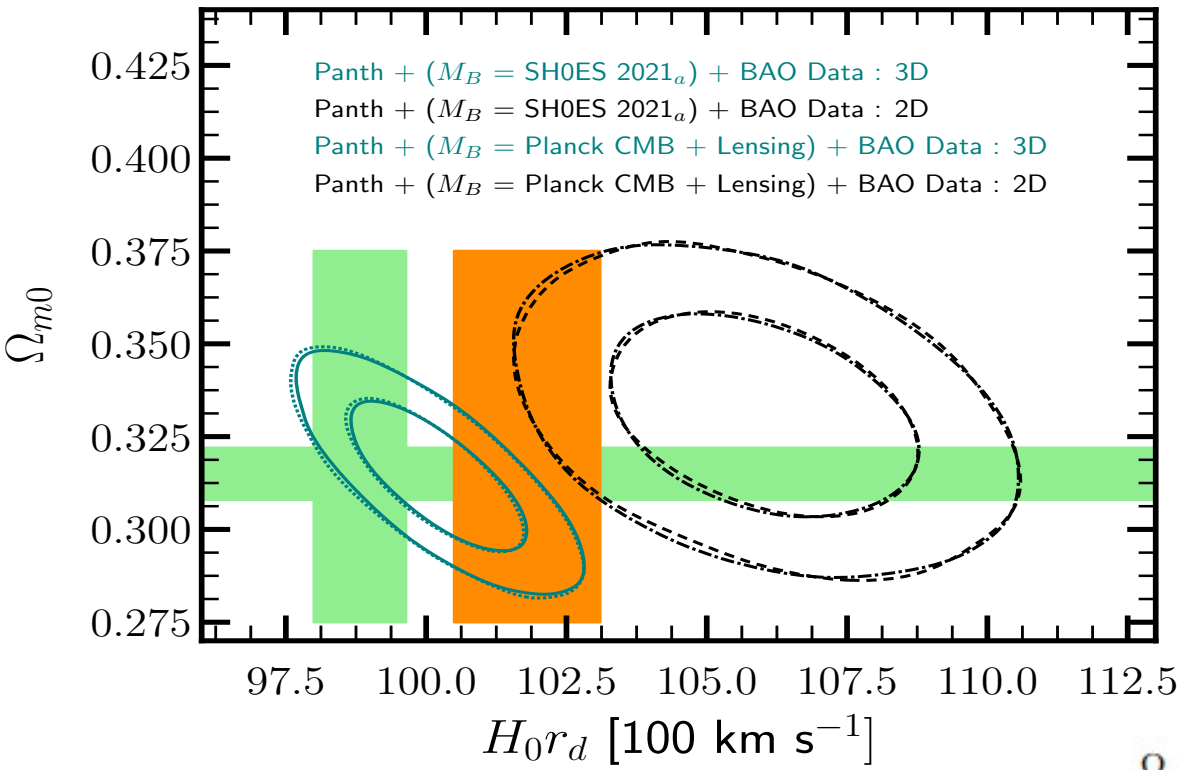
Result: Product $H_0 r_d$ from 2D and 3D BAO agrees within less than 1.5 sigma interval irrespective of SN calibration.

$$\left.\begin{aligned}\Omega_{m0} &= 0.314 \pm 0.0132 \\ r_d h &= 100.72 \pm 2.42 \text{ Mpc}\end{aligned}\right\} \text{BAO : 3D + PP}$$

$$\left.\begin{aligned}\Omega_{m0} &= 0.331 \pm 0.018 \\ r_d h &= 105.95 \pm 3.11 \text{ Mpc}\end{aligned}\right\} \text{BAO : 2D + PP}$$

MB= SH0ES'21$_a$

Results ◇



Assumption:
Standard Cosmological Model

Is it trouble to
- Standard Cosmological Model we assumed?

DESI BAO

CMB

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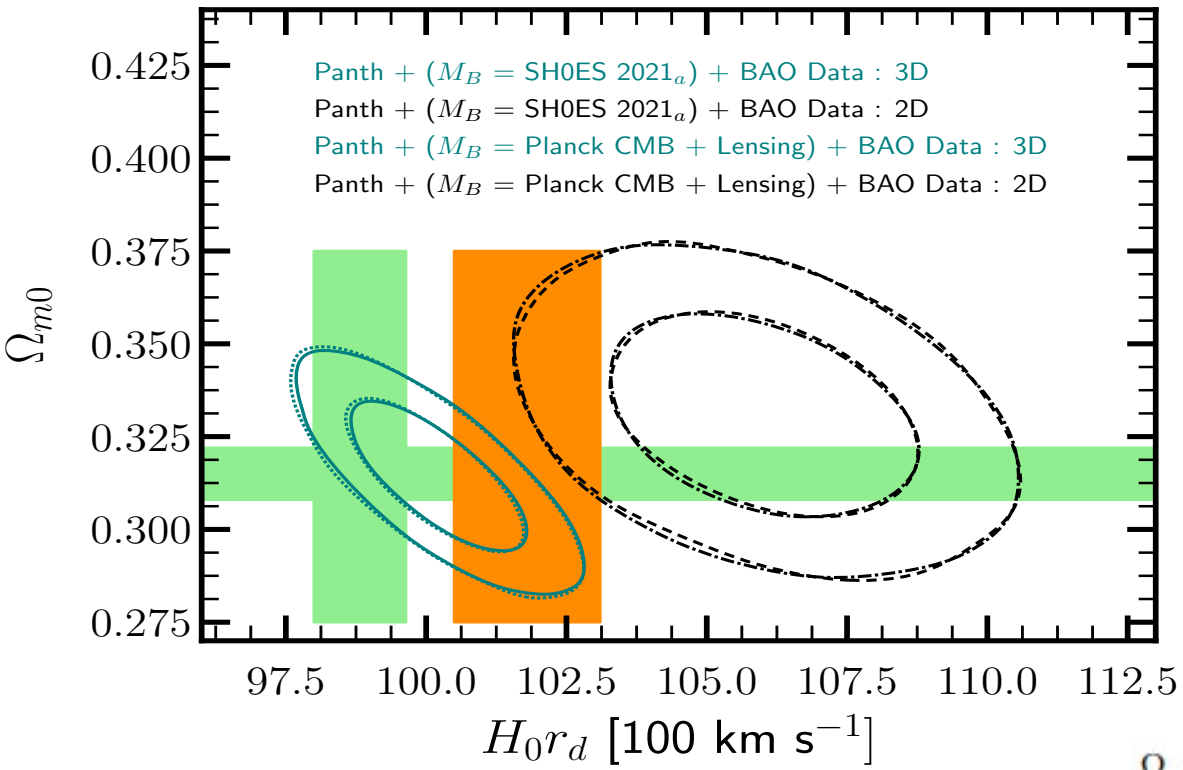

Assumption:
Standard Cosmological Model

Is it trouble to
- Standard Cosmological Model we assumed?

- Along with fiducial cosmology assumed in observations (to measure shift parameter alpha and true Theta Bao) ?

DESI BAO

CMB

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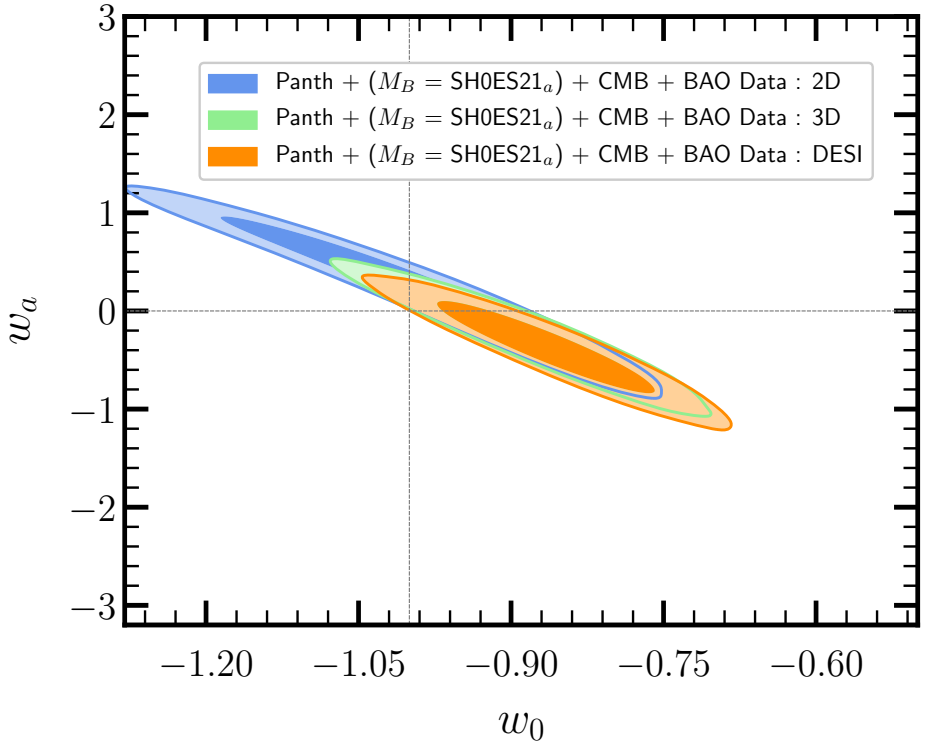
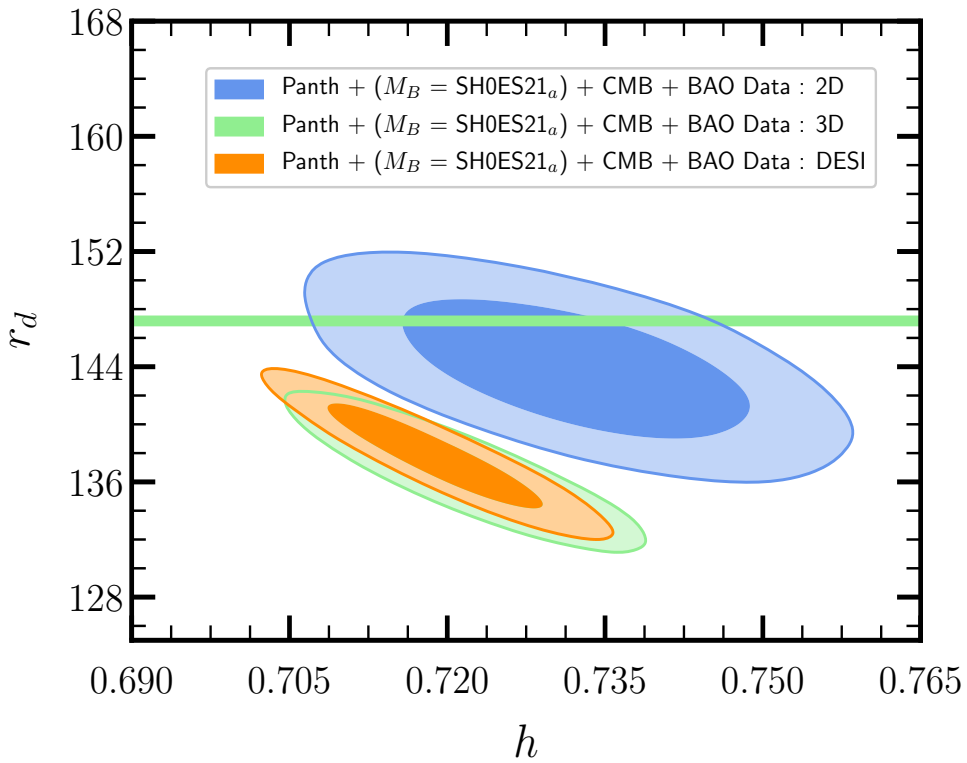
Results in comparison with DESI ◇



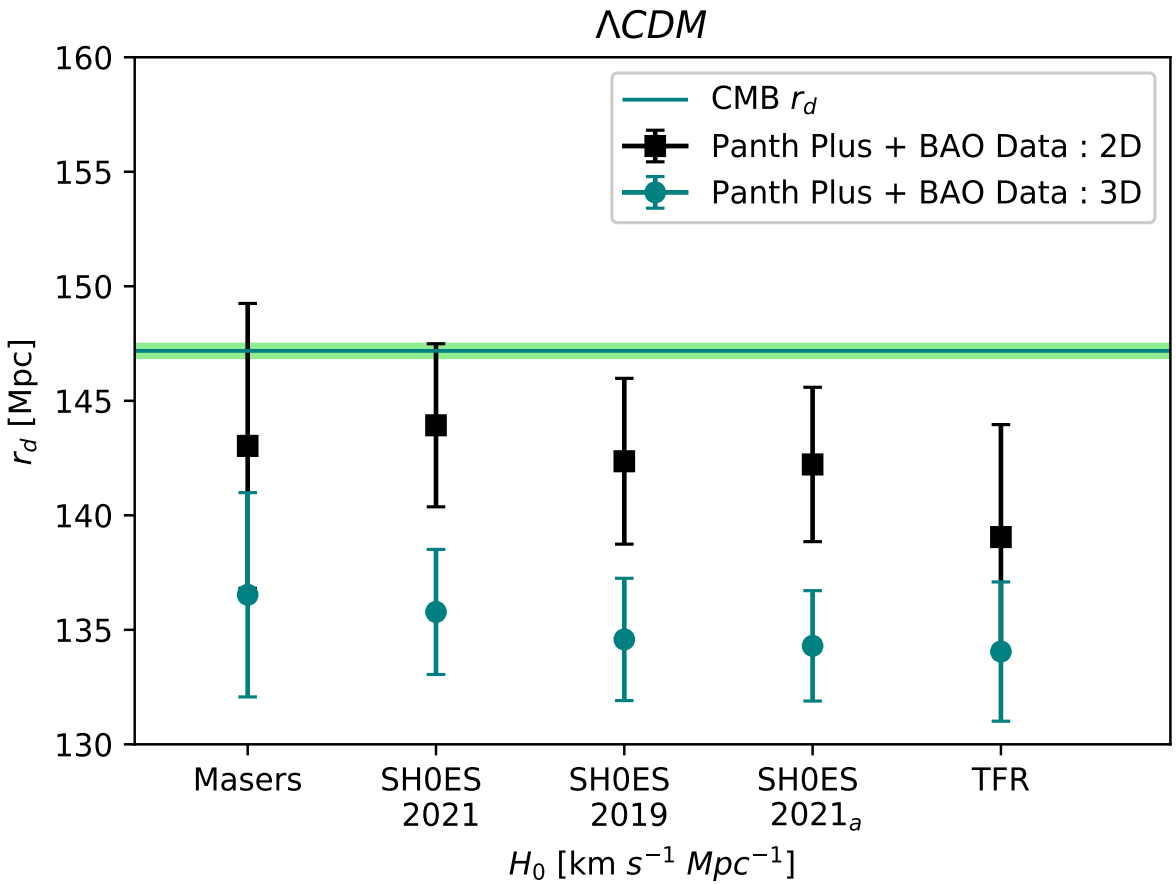


* Left: (w0,wa : -1.0,0) is at the two sigma boundary for BAO+CMB+Pantheon Plus sample.

* Right: r_d obtained from 2D BAO is compatible with Planck r_d (higher value) and higher H_0.

It is an artifact solely due to the relatively higher product $H_0 r_d$ measured by 2D BAO than 3D.

Concluding: What not to conclude? ◇



Reminder: 2D BAO measures higher $H_0 r_d$.

Result:

r_d obtained from 2D BAO is compatible with Planck r_d (higher value) and higher H_0.

Conclusion:

That is why, we should be very careful when we propose new cosmological models to solve cosmological tension such as Hubble tension while using 2D BAO Dataset.

Final Take-away ◇

- 2D BAO measures $H_0 r_d$ higher than 3D BAO and DESI analyses under standard ΛCDM cosmology
- Using 2D BAO, a higher H_0 compatible with SH0ES and a higher sound horizon r_d (compatible with Planck) can be achieved even within ΛCDM framework
- Caution must be taken while concluding about cosmological tensions specially while using 2D BAO dataset.
- Interpreting $\Omega_{m0} - hr_d$ plane may require physics beyond ΛCDM not just while using observational BAO data but also while observing and interpreting it.

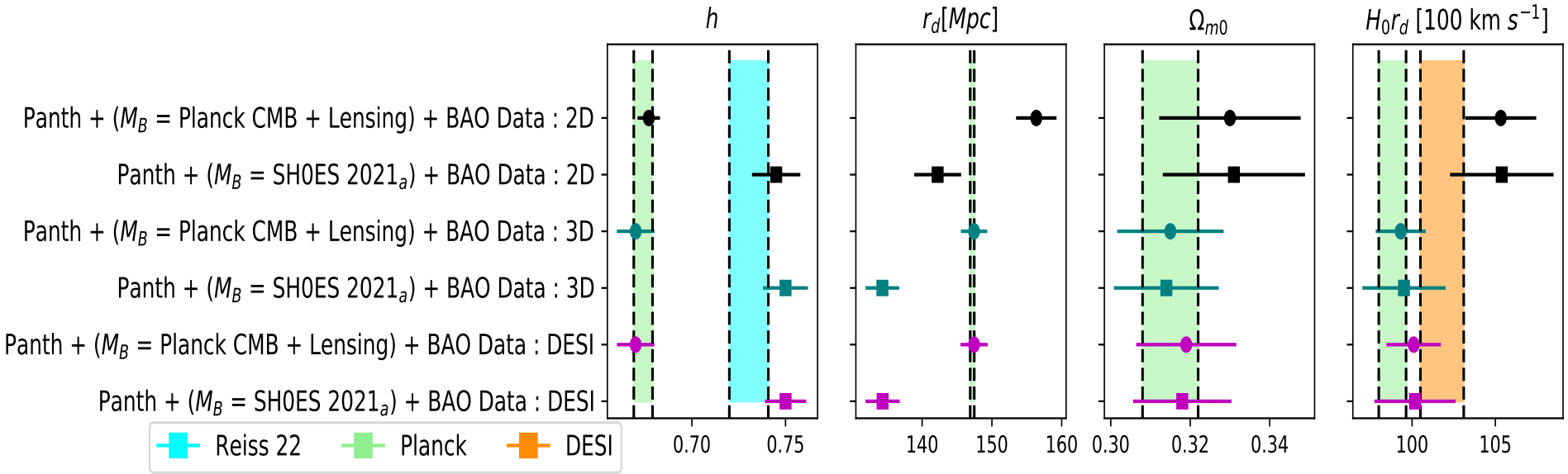
Future Directions! ◇

- Analysing 2D and 3D measurements from upcoming surveys such as DESI, Euclid, J-PAS may provide a better picture.

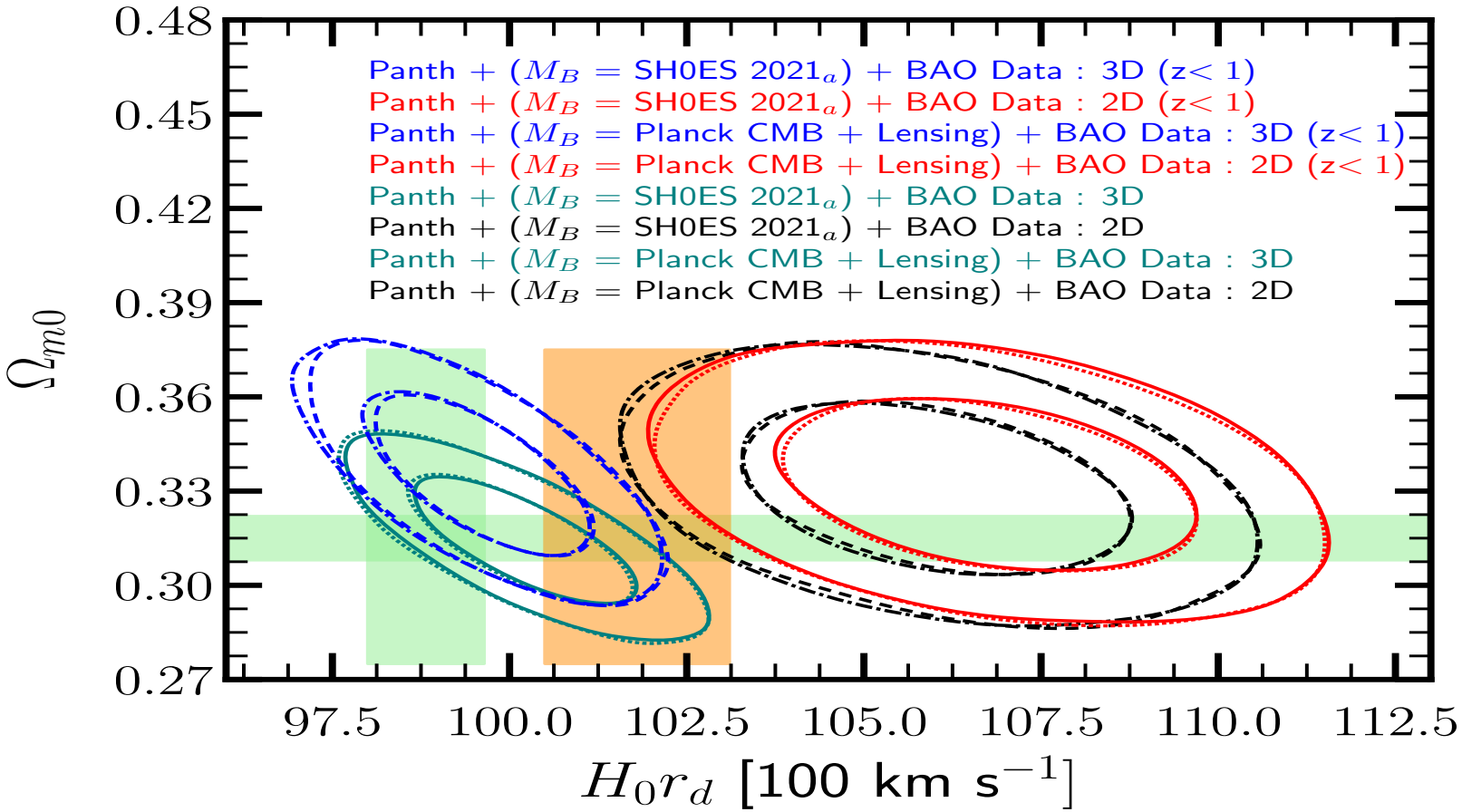
- One can benefit from less model dependent approaches (fiducical comology away from ΛCDM) while taking observations of BAO datasets.

THANK YOU!

Results ◇


h
$r_d[Mpc]$
Ω_{m0}
$H_0 r_d$ [100 km s^{-1}]
Panth + (M_B = Planck CMB + Lensing) + BAO Data : 2D
Panth + (M_B = SH0ES 2021$_a$) + BAO Data : 2D
Panth + (M_B = Planck CMB + Lensing) + BAO Data : 3D
Panth + (M_B = SH0ES 2021$_a$) + BAO Data : 3D
Panth + (M_B = Planck CMB + Lensing) + BAO Data : DESI
Panth + (M_B = SH0ES 2021$_a$) + BAO Data : DESI
Reiss 22
Planck
DESI
0.70
0.75
140
150
160
0.30
0.32
0.34
100
105

Results ◇


Panth + (M_B = SH0ES 2021$_a$) + BAO Data : 3D (z< 1)
Panth + (M_B = SH0ES 2021$_a$) + BAO Data : 2D (z< 1)
Panth + (M_B = Planck CMB + Lensing) + BAO Data : 3D (z< 1)
Panth + (M_B = Planck CMB + Lensing) + BAO Data : 2D (z< 1)
Panth + (M_B = SH0ES 2021$_a$) + BAO Data : 3D
Panth + (M_B = SH0ES 2021$_a$) + BAO Data : 2D
Panth + (M_B = Planck CMB + Lensing) + BAO Data : 3D
Panth + (M_B = Planck CMB + Lensing) + BAO Data : 2D
Ω_{m0}
0.48
0.45
0.42
0.39
0.36
0.33
0.30
0.27
97.5
100.0
102.5
105.0
107.5
110.0
112.5
$H_0 r_d$ [100 km s^{-1}]